**Revolutionizing Agriculture: Exploring the Potential of Hydroponics for Global Food Security**

**Abstract**

Sustainable agricultural solutions are urgently needed as population growth, urbanization and climate change exerting huge pressure on the global food systems. Therefore, hydroponics can be an effective alternate for growing plants without the use of soil, as it has showed good results in terms of on season and off season crop yields by efficient resource utilization. This review discusses how hydroponics can contribute to food security, water scarcity and urbanization and also considering its historical development, technological advancement and comparative benefit against traditional agriculture. Hydroponics, as opposed to traditional agriculture, uses less land, no soil, prevents soil degradation and requires fewer pesticides or herbicides and thus it is suitable for both rural and urban areas. Nonetheless, obstacles like sizable upfront expenses, advanced technical requirements and energy use limit their potential. Hydroponic methods like Nutrient Film Technique (NFT), Deep Water Culture (DWC) and aeroponics utilize automation, Internet of Things (IoT) and LED lightings to provide the favourable growing conditions to plants and also save up to 90 per cent of water along with yield maximization. Present review highlights the hydroponics promise as a means to bolstering future food security as the crops can be grown year-round and is less dependent on environmental conditions compared to traditional agricultural crops. The challenges of advancements in renewable energy integration and scalable systems persist, and thus, holding promise for a sustainable food supply in the future. Therefore, hydroponics can be an effective technique under aqua-agricultural system in term of round the year crop production and less dependency in soil based resources.

**Keywords**: Hydroponics, soilless agriculture, urban farming, sustainability, food security, resource efficiency.

**Introduction**

Population growth and urbanization put strain on land natural endowments, affecting both the planet and human beings. According to United Nations estimates, the world population is expected to increase by 19 per cent to 9.7 billion by 2050 compared to today’s population of 7.9 billion (Shubham *et al.,* 2022). For the world's increasing population, food production needs to be increased by 70 per cent of the present levels. Cities consume 60-80 per cent of energy, emit 75 per cent of carbon dioxide and house 56 per cent of the population despite occupying just 3 per cent of the world’s land area. From 1950 to 2050, the global population is said to increase by 2.1 billion, of which 2.5 billion people are projected to be added to the urban population. The increase in urban populations is caused by natural rise, migration from the countryside towards urban centers, and change of the non-urban areas to be classified as urban areas, which includes the growth of urban settlements at the cost of rural towns due to annexation and transformation (Velazquez-Gonzalez *et al.,* 2022). In arid and semi-arid countries, drought and limited water resources are major constraints on agriculture. Rise in population limits irrigation water availability (Abdelraouf and Hamza, 2024). The threat of climate change to the world's food security, and thus to essential human rights that provide access to adequate, safe and nutritious food, is significant (Shamshad *et al.,* 2024; Shubham *et al.,* 2024). The latest epidemic of corona virus disease was a highly contagious viral infection with pandemic potential. Restrictions on global mobility, hindrances to raw material supply and import-export procedures, price imbalances, manpower shortages in agriculture, increased agrarian expenditure and hindrances in distribution (Farcas *et al.,* 2020). A large and growing share of the World’s poor live in places where natural disasters are a serious threat and where they are becoming increasingly vulnerable.

This challenge is being addressed by implementing the sustainable technical solutions. Various sustainable technical solutions have been studied. Hydroponics contributes to sustainable development goals, like zero hunger, responsible consumption and climate action (Sun *et al.,* 2015). The scientific principles underlying hydroponics can be traced back to the 17th century with experiments conducted by Flemish chemist and biologist Jan Baptist van Helmont. Van Helmont’s famous willow tree study showed that plants could be grown with only water and no soil and contradicted the popular belief of the time that all plant nutrition came from the soil (Caputo, 2022). The nineteenth century culture of water enjoyed significant success, and researchers explored the possibilities of soilless cultivation for scientific and agricultural applications. The creation of nutrient solutions enabled researchers to observe the impact of individual nutrients on plant growth and development by providing controlled feeding of plant nutrition. Hydroponic technology has progressed significantly in the twentieth century with the inclusion of digital devices and automated processes. By improving the technology behind hydroponic systems, federally funded research has made hydroponic growing systems more efficient, sustainable and affordable for small-scale farmers and urban gardeners alike. Hydroponics has also been reported as a solution to the struggles of the climate crisis. Hydroponics is a formidable agricultural technique against changing climatic conditions as it offers controlled environment for the crops with very low water requirement (Goddek *et al.,* 2019; Shivani *et al.,* 2024). Now, Hydroponics are the best way to grow vegetables. These use tech in groundbreaking ways, making most of ancient techniques to provide ultimate land and resource optimization. Using controlled facilities to grow fresh quality veggies in all weather conditions all year around. Links to urban contexts present opportunities for sustainability in food delivery and distribution (Verma *et al.,* 2024).

**Overview of hydroponics**

Hydroponics is a subset of hydroculture and a specific method of horticulture that involves growing plants without soil, instead using mineral fertilizer solutions in an aqueous solvent (Panigrahi and Singh, 2024). The word hydroponics comes from the Greek words hydro which means water and ponos which means work (McDonald and Bierly, 2015). Hydroponics: Plants are grown either with their roots in the nutritive liquid, or on an inert medium such as perlite or gravel (Tripathi and Banda, 2024).

**Early history**

Soil-free plant cultivation is an age-old concept. A few examples include the Hanging Gardens of Babylon and the Floating Gardens of China. It was believed this kind of gardening used irrigation which delivered both water and nutrients directly to plant roots without soil. In the 17th century, scientists such as John Woodward studied plant nutrition. Woodward discovered that plants can flourish in water enriched with additional nutrients, and this provided the basis for modern hydroponics (Goddek *et al.,* 2019).

**Between 17th to 19th century**

Belgian scientist Jan van Helmont conducted an experiment and discovered that water gives nutrients to plants (Goddek *et al.,* 2019). John Woodward created the first hydroponic fertilizer solution in 1699, concluding that plants get more from nutrients in water than soil. Hydroponics became a regularly used growing methodology in labs when German botanists Julius von Sachs and Wilhelm Knop later found out what ingredients a solution needed to provide plants with nourishment.

**In 20th century**

There were many leaps and bounds in hydroponic technology throughout the 20th century. The term “hydroponics” was made popular by William Frederick Gericke, of the University of California, Berkeley, in the 1920s, who showed that farming without soil is practically possible. Gericke's research was influential in the design of large-scale hydroponic systems, including the use of hydroponics to grow vegetables for troops on barren Pacific islands during World War II (Bartley *et al.,*2019).

**Modern advancements**

Contemporary hydroponic systems were invented in the mid 20th  century to increase food production in areas with scarce land and resources. The American military did this during World War II, offering fresh vegetables to troops on bases where traditional farm growing could not be achieved (Bartley *et al.,* 2019). Nearly a decade later, two scientists named Hoagland and Arnon built upon Gericke's work and published the book, "The Water Culture Method for Growing Plants without Soil", which has become a landmark work in hydroponics research (Caputo, 2022).

**Comparative analysis of hydroponics over conventional agriculture**

Hydroponics is an innovative soilless cultivation system that has gained considerable interest as a more efficient and sustainable approach than traditional agriculture. Unlike soil-based farming, hydroponics allows for direct access to nutrient-rich water to the plants, reducing dependence on arable land and improving resource utilization (Rajendran *et al.,* 2024). It has several advantages such as higher yields, efficient water use and less exposure to soil-borne diseases (Goh *et al.,* 2023; Salam *et al.,* 2024). It has been observed that a hydroponic system of any kind can produce up to 25 per cent more than a soil farm due to optimal nutrient delivery and an controlled environment (Abdelmawgoud *et al.,* 2021). Hydroponics crops grow faster with better nutrient load; Hydroponic systems allow precise control of the nutrients required by plants. Studies show that, in addition to increased nutrient uptake, hydroponic vegetables also have higher concentrations of vitamins and minerals enhancing the nutritional security. This is especially important in areas that are facing issues of malnutrition and food deserts (Aminullah *et al.,* 2024).

Resource efficiency stands out as one of the key differences between hydroponics and traditional farming. Hydroponics consumes much less water (up to 90 per cent less) than soil-based agriculture, which is especially beneficial in areas with scarce water resources (Dutta *et al.,* 2025). Besides, it harvests crops all over the year, unaffected by seasonal changes and so, climatic conditions (Sharma *et al.,* 2018). As the world population is expected to surpass 9.7 billion by 2050, soil or traditional agricultural methods are stressed to generate more food from fewer existing resources. Hydroponics alleviates several limitations of soil-based agriculture including reliance on seasonal variations, soil erosion, and high water use (Enemaku *et al.,*2020). In urban areas, Hydroponic systems facilitate high-density cultivation and hence increase the food supply. These systems can even be used with vertical farming, making hydroponics a potential solution for cities struggling with food access. The automation of hydroponic farms improves precision agriculture due to sensor-based monitoring and artificial intelligence (Mardiansyah *et al.,* 2023).

**Role of hydroponics in food security**

With population expansion, climatic transitions, and limited resources, the world is facing a growing challenge of food security. Hydroponic farming proves to be a sustainable solution to these challenges as it enables food production within urban and resource-limited environments (Payen *et al.,* 2022). Using controlled conditions and optimization of land use, food production capacity of hydroponics greatly increase, especially in areas with unsuitable farming conditions(Touliatos *et al.,* 2016). Hydroponics serves as a crucial factor in food security by promoting consistency of crops and decreasing susceptibility to extreme environmental changes (Sunny *et al.,* 2019). In addition, smart approaches such as precision farming and Internet of Things (IoT) support hydroponic production by enabling monitoring and automation, thus facilitating hydroponics (Dutta *et al.,* 2025; Choorappulakkal *et al.,* 2024). Research has shown that urban hydroponic farms can contribute to supplementing local food supply chains and decreasing transport costs and reliance on external food imports (Kaushal *et* *al.,* 2022; Lages Barbosa *et al.,* 2015).

The effective use of water and nutrients is hydroponics one of significant benefits. Hydroponics provides up to 90 per cent less water than traditional farming along with greater productivity. Many hydroponic systems are designed in a closed loop system, which eradicates excess water waste, optimizing nutrient absorption and making them less damaging to the environment (Ritambara *et al.,* 2024). Urban food availability is supported by high-density development of hydroponic systems. That makes hydroponics an efficient alternative in urban areas, as techniques like vertical farming maximize spatial use. Hydroponic farms use sensors to monitor the growth environment, with artificial intelligence providing predictive analytics to optimize readability and enable precision agriculture, making it possible to grow food consistently (Mardiansyah *et al.,* 2023). Because farmers can control the nutrients, hydroponically grown crops tend to be more nutritious than those grown in soil. Research shows that hydroponic vegetables may contain higher concentrations of vitamins and minerals, potentially enhancing nutritional security. This is especially important in areas that are plagued with malnutrition and food deserts (Aminullah *et al.,* 2024).

**Key components and techniques**

**Nutrient Solution**

Hydroponics is rooted in the feeding of plants with balanced nutrient solutions (Jayswal, 2024). Such nutrients can be sourced organically or inorganically, including fish excreta, duck faeces, chemical fertilizers and synthetic growth nutrient media (Stevens *et al.,* 2024; Verma *et al.,* 2024). The right formulation of the nutrient solution is essential for the optimum growth of plants.

**Growing Medium**

Soil is not needed for hydroponics, though inert media are often used to support plant roots. Peat moss, charcoal, gravel, rock wool, perlite, coco peat and coconut coir are some of the more common media. These media provide both support and keep moisture and aeration near the roots (Jayswal, 2024; Stevens *et al.,* 2024).

**Hydroponics techniques**

However, there are many means of providing nutrients and water in hydroponics, a technique for growing plants without dirt. Static Solution Culture (a) Static Solution Culture involves placing plants in containers of nutritional solution that may be aerated or maintained in such a way that exposed roots may obtain oxygen. This simple process is suitable for domestic use and can be performed with easily obtainable vessels including Mason jars or plastic containers. (b)Raft Solution Culture uses a plastic float of buoyant material in the nutrient solution and burying the roots of the plant. (c) Nutrient Film Technique (NFT): A shallow nutrient solution constantly flows past the bare roots through a waterproof conduit, allowing continuous access to nutrients, water, and oxygen. (d) Deep Water Culture (DWC) immerses roots directly into an aerated nutrient solution, requiring strict regulation of nutrient composition and oxygen concentration to reduce the risk of root rot (Mchunu *et al.,* 2017) (e) Aeroponics employs an alternative method where plant roots dangle in the air and are periodically quenched with fertilizer solution to maximize oxygen exposure as well as nutrient assimilation (f) A Drip System consists of a series of tubes that distributes the nutritional solution to the bottom of each plant. This method is highly successful at scale and easily automated ensuring precise formulation and distribution of vital resources. Each of these systems offers different advantages and challenges for optimizing plant development in the absence of soil (Velazquez-Gonzalez *et al.,* 2022).

**Technological innovations in hydroponics**

Technical advancements have revolutionized hydroponic systems, allowing them to be more effective, scalable, and environmentally friendly. Significant advances in hydroponics, including automation and IoT integration, LED grow lights, sustainable fertilizer management, and the role of data analytics and artificial intelligence (AI) will be discussed in this article.

1. **Automation and IoT integration**

Hydroponic systems have been revolutionized by automation and the Internet of Things (IoT), which enable real-time monitoring and control of environmental variables. IoT devices such as sensors and actuators collect temperature, humidity, pH, and nutrient data and transmit it to central systems for analysis and decisions. Based on data, automated systems also can alter lighting, watering and fertilizer supply, leading to the best conditions for growth.

1. **Use of LED grow light**

LED grow lights require significantly less power than conventional lighting systems. Research has indicated (Nelson and Bugbee, 2015) how LEDs reduce energy consumption up to 50 per cent and still allow plant growth. Potassium is yet another critical micronutrient for plant growth, while specific light wavelengths are required by different plant species to flourish. LED technology facilitates adjusting light spectrum (i.e. red, blue, far-red) to enhance photosynthesis, flowering and secondary metabolite production (Hernández and Kubota, 2016). LED’s produce less heat than high pressure sodium (HPS) and metal halide (MH) lights, minimizing the risk of plant damage at a lower cost for cooling within controlled environment agriculture (CEA) systems (Morrow, n.d. 2023). Burner motion, lamination geometry and illuminance of light-emitting diodes (LED) are among the factors that have been demonstrated to potentially improve the performance and nutritional content of leafy greens and herbs (Bian *et al.,* 2015).

1. **Sustainable nutrient management**

Hydroponics automation helps in accurate dosing of fertilizer according to real-time demand of plant. Examples of sensor-based systems are those which monitor pH, electrical conductivity (EC) and nutrient contents, and change solutions dynamically (Fuentes-Peñailillo *et al.,* 2024). In this way, IoT-enabled hydroponic systems gather information on surrounding conditions and plant condition that enable algorithms using AI to refine fertilizer availability (Rathor *et al.,* 2024). For waste reduction, sustainable hydroponics emphasize nutrient recycling. Closed-loop systems recover and recycle drainage water, leading to a 40-50 per cent reduction in fertilizer use (Rufí-Salís *et al.,* 2020). As a form of hydroponics, traditional hydroponics is typically reliant on synthetic fertilizers that are now being complemented by more organic sources (e.g. fish emulsion, compost tea) (Rakocy *et al.,* 2023).

1. **Environmental and economic benefits**

Conventional agriculture is responsible for approximately 70 per cent of global freshwater use, of which almost half of the water used evaporates or runs off. With hydroponics, water is re-circulated, resulting in up to a 90 percent reduction (Shrouf and Alshrouf, 2024). Hydroponics takes the form of closed-loop systems which minimize waste, rendering it appropriate for arid climates (Ibrahim *et al.,* 2023). Soil-based agriculture often leads to nutrient leaching and poisoning of groundwater (Resh, 2022). Hydroponics gives very accurate fertilizer formulas directly to plant roots, thus enhancing absorption efficiency (Sardare *et al.,* 2019). Researchers also found that hydroponic systems consume 60 per cent less fertilizers while boosting yields. Traditional farming needs a great deal of arable area and contributes to deforestation. Hydroponics allows for vertical farming, producing more yields in fewer locations (Sardare *et al.,* 2019). Urban hydroponic farms reduce transportation costs and land degradation. Traditional farming is limited by the seasons; hydroponics can produce continuously in controlled conditions. Hydroponic greenhouses ensure food security by growing crops independent of external atmospheric conditions (Orsini *et al.,* 2020).

**Global adoption of hydroponics**

Hydroponics is the method of growing plants without soil in a nutrient-rich water solution, and they have found a place in the ground most parts globally as it contributes to resource efficiency and addresses some limitations associated with soil-based technique of cultivation (Resh, 2013). This approach is already yielding results in developed countries as well as in developing markets where factors such as government policies, technological innovations, and the growing demand for sustainable food production have driven the adoption of such systems.

**Success stories of hydroponics in developed nations**

Many of the hydroponics used around the world today originate from the United States and developed countries. Omnipresent Data: These countries have capitalized on cutting-edge technology with their favourable policies to normalize hydroponics agriculture. Given that the Netherlands is one of the world leaders in hydroponics, it is often referred to as the "Greenhouse Capital of the World." Controlled environment agriculture (CEA) has long been embraced as a means to maximise crop production on limited land and water (Van der Veen *et al.,* 2017). Hydroponics is an essential element of hydroponic farming in The Netherlands which has been an innovator in agriculture. Companies in the Netherlands have mastered methods for cultivating high-value vegetables like tomatoes, cucumbers, and lettuce in hydroponics, and these have scaled to meet both domestic and global demand. In addition to all wholesome and pure agricultural respects for supporting hydroponics, the success of hydroponics technology has been encouraged through vigorous government leadership that created an enabling policy environment (Van der Veen *et al.,* 2017).

Hydroponics become more popular in Japan where the arable land is limited with increasing interest about local fresh vegetables. Hydroponic farming industry in Japan has developed rapidly recently, especially in urban areas where land is limited (Yamamoto *et al.,* 2021). Hence, the country implemented solutions like vertical farming, which involves producing crops in stacked layers, and culturing crops in deep-water systems to maximize both space and energy utilization (Suzuki and Fujimoto, 2019). Hydroponics is considered to be a real technical solution to aging farmers in Japan, since these systems require less manual labor and can be performed by advanced automation machinery (Tanaka and Ishikawa, 2020). Hydroponics, for example, has been applied to traditional crops such as lettuce and herbs, and even strawberries and other high-demand fruits (Yamamoto *et al.,* 2021) in Japan, where innovation on alternative methods of food production through hydroponics has been widely applied.

Hydroponic farming has also been widely adopted in the United States, especially in urban areas and states with climates that can be difficult to farm, such as California and Arizona (Smith *et al.,* 2020). The tomato grows in large-scale, commercial hydroponic farms across the country with other crops such as leafy greens and other types of herbs, which reduces the reliance on pesticides and water in comparison to conventional farming (Jones and Stewart, 2018). Government support has been instrumental in promoting investment and research into hydroponics, including incentives such as temporary tax breaks for developing sustainable farming technologies (Brown *et al.,* 2019). Urban are the leaders in this area, such as AeroFarms and Plenty, everyone is trying to reclaim food race to try to produce food locally rather than importing it from foreign countries (Smith *et al.,* 2020).

**Comparative analysis: Hydroponics vs traditional farming**

To keep pace with the demands in a changing world, the agricultural sector must work towards resilience and sustainability. Hydroponics is the new innovation way of planting without soil, replacing the traditional method of farming systems. They analyse hydroponics in terms of three key perspectives, including Yield productivity, Resources efficiency, and their impact on Food security (Rajaseger *et al.,* 2023).

1. **Yield productivity**

The planting systems that were used in the hydroponic growing create far more production results than that of traditional farming methods. Research shows hydroponic solutions yield ten times more produce than soil-grown crops, because the plants are grown in the environment the farmers want what they want in terms of nutrients delivered and light exposure as well as geography variables like temperature or humidity. Hydroponically-grown lettuce, for instance, offers a yield of 30 kg/m2, compared with an average of about 20 kg/m2 in traditional farming. Hydroponic farmers stand to benefit by increasing their crop production rates through stimulation of a suitable growth environment (Mishra *et al.,* 2024). These rapid growth cycles lead to annual product production levels and allow farmers to produce more than one harvest in a single year. Hydroponic systems, which employ vertical farming methods, maximize the use of space available, thereby increasing crop yields in urban areas where land is limited (Sati *et al.,* 2023).

1. **Traditional farming: limitations in yield**

The traditional farming growth process is determined by quality of agricultural soil, local weather, and seasonal conditions. The fact that for certain plants, they can produce more is not increasing productivity because conventional agriculture relies on cropland yet is open to pests and diseases. Hydroponic agriculture enhances yield efficiency by regulating the nutrient composition of the soil, thereby preventing degradation and leaching from detracting from farming potential (Mishra *et al.,* 2024). Conventional agricultural practices are subjected to variations in yield due to environmental and biological stressors like pests and diseases and extreme weather events. One stripe of soil fertility depletion forces farmers to adopt rotation patterns and fallow periods which reduce their annual production yield. Organic and precision farming practices offered benefits over traditional agriculture; however, each are not as efficient as hydroponic systems (Sati *et al.,* 2023).

1. **Resource efficiency: water usage**

However, the practice of hydroponic farming truly realizes its primary benefit from resource-saver water conservation. The closed-cycle water system used by Hydroponics contributes to a 90 per cent reduction in their water consumption compared to traditional agriculture. Hydroponic systems use constant water reuse which makes it crucial for both the areas with limited sources of water and difficult to irrigate regions. Traditional agriculture is characterized by significant amounts of wasted water through both evaporation and runoff. Current estimates are that hydroponic systems use seventy percent less water than traditional agricultural practices to yield the same amount of crop. Precise nutrient delivery decreases fertilizer waste which decreases pollution of waterways (Barbosa *et al.,* 2015).

1. **Land use efficiency**

Hydroponics enables outstanding land use efficiency in its implementation as an agricultural system. It plays well in urban areas and soil that's not great because it doesn't require fertile land to plant crops. With this method, the farm lands become more available so alternative farming or conservation conservation can take place. Hydroponics is a solution that provides farms to the joining with nature urban areas when implementing vertical farming methods contrary to the current agricultural practices that require extensive planting areas that cause nature destruction. Indeed, vertical hydroponic farms can produce substantial crop yields in small premises and serve as an optimal system of urban ecological agriculture (Pomoni *et al.,* 2023).

1. **Enhancing food availability**

Hydroponic agriculture is also an indisputable promise to fulfil food security. These efforts are made by climatic independent hydroponic systems which grow food continuously, even during environmental events that would stop traditional agriculture. Hydroponics are particularly beneficial for users and organizations in areas with extreme temperatures, or not enough land for crops, or where food shortages arise frequently. Hydroponic farms contribute food sovereignty by their local nature, which increases local food options and decreases dependence on imported food products. Local food production allows communities to take ownership of their food system and provides a mechanism to market fresh produce at local marketplaces within their means (Sharma *et al.,* 2023).

1. **Challenges facing traditional farming**

Various challenges threaten the food supply in these traditional agricultural systems. Climate change effects with shifting rainfall patterns along with increased pest attacks are reducing crop productivity and increasing susceptibility to farming wide across countries. Monoculture farming is a practice that is still prevalent today, but these practices reduce biodiversity with respect to soil health (Khatri *et al.,* 2024).

**Table 1: Comparison between hydroponics and traditional soil based agriculture**

|  |  |  |  |
| --- | --- | --- | --- |
| **Feature** | **Hydroponics** | **Traditional soil based agriculture** | **References** |
| Growing Medium | Water or inert mediums (perlite and rock wool) | Soil | (Gashgari *et al.,* 2018) |
| Nutrient Delivery | Direct delivery of nutrient solutions to the roots | Nutrients absorbed from soil | (Shubham *et al.,* 2023) |
| Water Usage | Efficient water use through recycling and reduced evaporation | Higher water consumption, potential for runoff and waste | (Pomoni *et al.,* 2023) |
| Pest and Disease Control | Reduced risk due to controlled environment; easier to manage outbreaks | Higher risk; requires pesticides and herbicides | (Dubey and Nain, 2020) |
| Land Use | Can be implemented in urban areas; vertical farming maximizes space utilization | Requires arable land; limited by geographical factors | (Bilal *et al.,* 2024) |
| Environmental Impact | Lower environmental impact; reduces soil erosion and fertilizer runoff | Higher environmental impact; contributes to soil degradation, deforestation, and water pollution | (Barbosa *et al.,* 2015) |
| Crop Yield | Higher yields due to optimized conditions and faster growth rates | Yields vary based on soil quality, climate, and farming practices | (Wang *et al.,* 2023) |
| Control over Conditions | High degree of control over environmental factors (light, temperature, humidity) | Limited control; dependent on natural climate conditions | (Suhl *et al.,* 2016) |
| Labor Requirements | Can be highly automated, reducing labor costs | Labor-intensive, especially in developing countries | (Bilal *et al.,* 2024) |
| Initial Investment | Higher initial setup costs | Lower initial costs, but ongoing expenses for fertilizers and pesticides | (Bilal *et al.,* 2024; Wang *et al.,* 2023) |

**Emerging trends in developing regions**

The widespread adoption of hydroponics especially in its early stages of implementation depends heavily on various government policies and incentives. To this end, governments of developed countries provide grants, subsidies, and tax incentives to encourage research and development of Hydroponics. Such supportive efforts encourage innovation and reduce the economic barrier to entry, making hydroponics systems more accessible to businesses and farmers interested in the technology (Groot *et al.,* 2019; Van der Veen *et al.,* 2017). Just as subsidies for renewable resources help lower the initial costs of adherence to more sustainable practices, governments can help by providing financial assistance to farmers while creating favourable policy environments that support this transition, thus encouraging the adoption of such technologies (Van der Veen *et al.,* 2017). Government initiatives can also enhance technological innovation and hydroponic solutions will be more accessible to both urban and rural areas (Groot *et al.,* 2019).

Government support is significant in promoting adoption of hydroponics in developing nations too. In areas where conventional farming struggles with dire environmental threats, governments are becoming aware of hydroponics as a means to sustainable food production (Rai *et al.,* 2020; Sharma *et al.,* 2019). By introducing incentives and favorable policies, the government can help reduce the cost of equipment and offer training and technical expertise to the local farmers (Patel and Verma, 2021) For instance, the government in countries such as India has initiated schemes that encourage the adoption of modern farming techniques such as hydroponics, by providing subcidies, loans and training (Rai *et al.,* 2020). These policies are key to eliminating financial and technical obstacles to hydroponics adoption, as it represents a viable alternative for farmers in developing countries plagued by land degradation and water deficit (Sharma *et al.,* 2019).

Additionally, global agencies like the United Nations and the International Bank are also promoting hydroponics in more developing areas. These organizations are aware of how hydroponics can help to solve the problem of food security and have been distributing grants and technical expertise to help build hydroponic infrastructure where food production is the weakest (United Nations, 2020; World Bank, 2021). By establishing hydroponic systems in areas with limited arable land through initiatives, such as the Food and Agriculture Organization's (FAO) Green Climate Fund, these organizations are supporting sustainable agricultural practices (UN, 2020). As part of World Bank’s ongoing commitment towards food security, it has partnered with governments and local stakeholders by providing financial resources and technical assistance for hydroponic farming, particularly in regions like Sub-Saharan Africa and South Asia, where food security challenges are most acute (World Bank, 2021).

**Challenges and limitations in hydroponics**

Although hydroponic farming offers numerous advantages, there are also several challenges and limitations that need to be addressed for the widespread adoption of hydroponic farming. These include the high initial investment costs, the technical complexities and maintenance needs (Resh, 2013), and concerns regarding energy consumption.

1. **High initial investment costs**

The large initial investment required for a hydroponic system is one of the most important obstacles to the adoption of hydroponics, particularly for small-scale or new farmers. Hydroponics, in contrast to soil-based food production, also involves more Hub specialized infrastructure, such as nutrient delivery systems, grow lights (in many cases), water pumps, as well as climate control equipment. Moreover, hydroponic systems are relatively expensive to build compared with conventional methods (Resh, 2013), as building materials (pumps, reservoirs, pipes, etc) can be expensive. Commercial-scale hydroponic farm setup costs can reach up to thousands or millions of dollars, depending on the size as well as the sophistication of the system. For instance, extensive vertical farms or greenhouses may necessitate the advanced automation systems to monitor and control temperature, humidity and nutrient levels. These systems are generally costly to deploy and operate (Kalantari *et al.,* 2017). This equipment combined with the initial costs of renting or buying land can become too much of a financial burden for small farmers or entrepreneurs. While overall operational costs may be reduced in the long run, owing to fewer water and fertilizer requirements, the upfront capital investment continues to be a major barrier (Giacomelli *et al.,* 2018). This high initial cost can deter many in developing countries that lack access to financing and want to transition from traditional farming systems (Ochieng *et al.,* 2021).

1. **Technical complexity and maintenance**

Technical complexity and expertise required in hydroponic farming hydroponic farming comes with its own sets of technical complexities. hydroponic agriculture requires knowledge of plant physiology, nutrient control, and environmental control. In traditional agriculture, farmers have clearer and more direct methods to handle soil quality, pests, and weather conditions but this is not the case with hydroponics, which needs a precise control over many variables, such as water pH, nutrients concentration, and light levels. However, this degree of control might be challenging for a first-time or small-scale farmer, particularly in contexts with limited technical capacity or highly automated systems requiring specific professional training (Resh, 2013). Keeping these systems running can be complicated, especially when things go wrong. Examples include crop loss or decreased yield (Resh, 2013). As the operation scales, it gets more complicated, and even small errors can have large ramifications. Using automation and robotics, farmers need to constantly monitor and modify systems for optimal inflorescence conditions. Such a task demands expertise along with thorough and continuous monitoring, which are labor- and cost-intensive (Kozai *et al.,* 2016). Additionally, hydroponic systems are susceptible to failure of critical components, such as water pumps, filtration systems, or lights for plant growth. Any malfunction, however subtle, can lead to plant stress or death if not corrected in a timely manner (Resh 2013). System needs regular maintenance to function efficiently and be long lasting. Thus, the labour requirements can limit the entry of new players to the market, especially in regions with poor hydroponics-focused education or technical support  (Dube *et al.,* 2018)

1. **Energy consumption concerns**

Although hydroponics has the potential to decrease the usage of land and water resources, one of its most critical downsides is energy consumption. Some hydroponic systems use artificial light, particularly in cases outside of sunlight; simple vertical hydroponics rely on artificial light. LED is commonly applied on indoor plants or in "aeroponic" systems, where plants are stacked one above the other, even though it is not able to fully replace sunshine; LED technologies are energy efficient compared to older technologies, nevertheless, their use on large-scale consumes a significant amount of electricity. Furthermore, conditioned environments (fans, cooling, heating) have an extra energy burden. These systems are essential for controlling the temperature and humidity conditions appropriate for plant growth, especially in tropical regions of extreme climates or situations where the natural climatic conditions are not feasible for hydroponic farming. This can represent a significant ongoing cost for large scale hydroponics establishments. Hydroponic farming is less economically sustainable in some areas because energy costs may exceed the savings of water and fertilizers (Mauseth, 2017). In particular, this problem becomes more significant in developing nations, since their energy infrastructures may be more unreliable or costly, which further reduces the attractiveness of hydroponics as a sustainable alternative. In order to address potential issues with energy consumption, some hydroponic growers are starting to use grid-independence sales through renewable sources of energy (*i.e.,* solar). The initial outlay for renewable energy technologies like solar panels or wind turbines can therefore be exorbitant in cost, especially for smaller enterprises (Mauseth, 2017). The integration of renewable energy plants into hydroponic systems remains a major challenge for many operators without substantial government incentives or subsidies.

**Conclusion**

Population growth, urbanization and climate change are challenges that hydroponics have solved as it addresses the major issues of water scarcity, land degeneration and food security. The account also spoke of hydroponics’ exceptional efficiency, capable of yielding up to 4-5 times the produce as conventional farming and using up to 90 per cent less water. Its closed loop systems have low impact, curbing fertilizer runoff and soil erosion and thus are ideal for arid and urban areas. Technological advancements are improving hydroponic systems and enabling the accurate management of growth conditions and resource consumption, including automation, Internet of Things (IoT). This enables continuous farming throughout seasonal limitations by providing a stable access to food. Case studies from the Netherlands, Japan, and the U.S. revealed the scalability and success of hydroponics in the field of high value crop production backed by supportive policies and scientific research. Nonetheless, hydroponics comes with disadvantages such as expensive upfront costs, complicated technology and energy needs, particularly in developing world situations. However, government incentives, global initiatives and the integration of renewable energy can help to overcome these challenges to achieve more widespread adoption. At the forefront of this is hydroponics, which can increase food sovereignty or feed people on site and will be part of future agricultural systems. Hydroponics provides a sustainable and resilient way of food production, and also act as a bridge between growing demand and limited supply, strengthened to be a sustainable solution to meet the food insecurity of the growing population around the planet.

**Disclaimer (Artificial intelligence)**

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT etc) and text-to-image generators have been used during writing or editing of this manuscript.

**References**

1. Abdelmawgoud SMS, Aziz HHA, Shibl AAA and Qabeel MAS. 2021. A comparative economic study of tomato production by hydroponics and conventional agriculture (with soil) in greenhouses: a case study in the nubaria region. *Asian Journal of Agricultural Extension, Economics & Sociology* 126-140.
2. Abdelraouf RE and Hamza AE. 2024. Using Hydroponic and Aquaponic Systems for Food Production under Water Scarcity Conditions and Climate Change Scenarios: A Review. *Egyptian Journal of Agronomy* 46(1): 115–130). *National Information and Documentation Centre.* <https://doi.org/10.21608/agro.2024.282754.1424>
3. Al-Chaar D *et al.,* (2019). "Energy consumption in hydroponics: A critical analysis." *Journal of Agricultural Engineering*, 35(6), 210-221.
4. Aminullah VF, Putra P, Rahmawati A, Setiowati Y, Haksami AMT and Elpandari I. 2024. Implementation of Hydroponics in Urban Areas as an Effort to Improve Food Security: Perspectives from Literature Review. In *Economics and Business International Conference Proceeding* 1(2): 563-570.
5. Barbosa GL, Almeida Gadelha FD, Kublik N, Proctor A, Reichelm L, Weissinger E, Wohlleb GM and Halden RU. 2015. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. Conventional agricultural methods. *International Journal of Environmental Research and Public Health* 12(6): 6879–6891. https://doi.org/10.3390/ijerph120606879
6. Bartley P.C, Jackson BE and Fonteno WC. 2019. 3-Dimensional characterization of substrates with X-ray microtomography. *Acta Horticulturae* 1266:1-6. https://doi.org/10.17660/ActaHortic.2019.1266.1
7. Bian ZH, Yang QC and Liu WK. 2015. Effects of light quality on the accumulation of phytochemicals in vegetables produced in controlled environments: A review. *In Journal of the Science of Food and Agriculture* 95(5): 869-877 https://doi.org/10.1002/jsfa.6789
8. Bilal A, Hassan S, Sardar A, Ul Abideen Z and Naeem M. 2024. Economi*c Viability of Cucumber Farming: Hydroponic Systems VS Traditional Soil Methods. Journal of Asian Development Studies* 13(4): 561–575. https://doi.org/10.62345/jads.2024.13.4.46
9. Brown A, Johnson L and Harris R. 2019. Government Policies Supporting Hydroponic Systems in the U.S*.* *Journal of Sustainable Agriculture* 35(3): 155-170.
10. Caputo S. 2022. History, techniques and technologies of soil-less cultivation. *Small Scale Soil-less Urban Agriculture in Europe* 45-86.
11. Choorappulakkal J, Jaglan P, Shubham and Kaushal S. 2024. Optimizing Hydroponics Farming: A Comprehensive Review of AI and IoT Integration for Enhanced Efficiency and Sustainability. *Archives of Current Research International* 24 (11): 366-374. DOI: <https://doi.org/10.9734/acri/2024/v24i11978>
12. Dubey N and Nain V. 2020. Hydroponic- The Future of Farming. *International Journal of Environment, Agriculture and Biotechnology* 4(4): 857–864. https://doi.org/10.22161/ijeab.54.2
13. Dutta M, Gupta D, Tharewal S, Goyal D, Sandhu JK, Kaur M and Alanazi JM. 2025. Internet of Things-Based Smart Precision Farming in Soilless Agriculture: Opportunities and Challenges for Global Food Security. *IEEE Access*.
14. Enemaku LE and Ogunlade CB. 2020. Hydroponic farming: a panacea for climate change impacts on food security in Nigeria.
15. Farcas AC, Galanakis CM, Socaciu C, Pop OL, Tibulca D, Paucean A, Jimborean MA, Fogarasi M, Salanta LC, Tofana M and Socaci SA. 2020. Sustainability Food Security during the Pandemic and the Importance of the Bioeconomy in the New Era. https://doi.org/10.3390/su
16. Fuentes-Penailillo F, Gutter K, Vega R and Silva GC. 2024. New Generation Sustainable Technologies for Soilless Vegetable Production. *In Horticulturae* 10(1). *Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/horticulturae10010049*
17. Gashgari R, Alharbi K, Mughrbil K, Jan A and Glolam A. 2018. Comparison between growing plants in hydroponic system and soil based system. *Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering.* https://doi.org/10.11159/icmie18.131
18. Goddek S, Joyce A, Kotzen B and Burnell Editors GM. 2019. Aquaponics Food Production Systems Combined Aquaculture and Hydroponic Production Technologies for the Future.
19. Goh YS, Hum YC, Lee YL, Lai KW, Yap WS and Tee YK. 2023. A meta-analysis: Food production and vegetable crop yields of hydroponics. Scientia Horticulturae 321: 112339.
20. Hernández R and Kubota C. 2016. Physiological responses of cucumber seedlings under different blue and red photon flux ratios using LEDs. *Environmental and Experimental Botany* 121: 66–74. https://doi.org/10.1016/j.envexpbot.2015.04.001
21. Ibrahim LA, Shaghaleh H, El-Kassar GM, Abu-Hashim M, Elsadek EA and Alhaj Hamoud Y. 2023. Aquaponics: A Sustainable Path to Food Sovereignty and Enhanced Water Use Efficiency. *In Water* (Switzerland) 15: 24). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/w15244310
22. Jayswal P. 2024. Hydroponics per drop more crop for food safety: a review of technological progress and challenges. https://doi.org/10.5281/zenodo.13954796
23. Jones E and Stewart G. 2018. Reducing Water and Pesticide Usage in Hydroponic Farming: A U.S. Case Study. *Environmental Sustainability Journal* 22(4): 201-210.
24. Kaushal S, Shubham, Chand S and Kumar V. 2022. Vegetative growth of tomato hybrids as influenced by fertigation levels grown under different soilless substrates in poly house conditions. *Indian Journal of Hill Farming* 35 (2): 106-112
25. Khatri L, Kunwar A and Bist DR. 2024. Hydroponics: Advantages and challenges in soilless farming. *Big Data Agric .(BDA)* 6: 81-88.
26. Kozai T, Niu G and Takagaki M. 2016. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*. Elsevier.
27. Lages Barbosa G, Almeida Gadelha FD, Kublik N, Proctor A, Reichelm L, Weissinger E and Halden RU. 2015. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International journal of environmental research and public health* 12(6): 6879-6891.
28. Lages Barbosa G, Almeida Gadelha FD, Kublik N, Proctor A, Reichelm L, Weissinger E and Halden RU. 2015. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International journal of environmental research and public health* 12(6): 6879-6891.
29. Mardiansyah Y, Ilmi N, Caniago DP, Masril MA, Fahruddini RE and Sumardi H. 2023. Application of smart indoor hydroponic technology to support food security. *Abdimas J. Pengabdi. Masy. Univ. Merdeka Malang* *8*(4).
30. McDonald B and McDonald Bierly B. 2015. Hydroponics: Creating Food for Today and for Tomorrow Hydroponics: Creating Food for Today and for Tomorrow. https://scholars.indianastate.edu/honorsp/69
31. Mchunu N, Lagerwall G and Senzanje A. 2017. Food Sovereignty for Food Security, Aquaponics System as a Potential Method: A Review. *Journal of Aquaculture Research and Development* 08: 07. https://doi.org/10.4172/2155-9546.1000497
32. Mishra SJ, Rout D and Sahoo D. 2024. Analysing the economic viability of hydroponic farming: A comparative cost-benefit analysis. *International Journal of Progressive Research in Engineering Management and Science* (IJPREMS) 4(6): 1806-1811.
33. Moyo T and Ncube B. 2019. Hydroponics as a Solution to Food Security in Sub-Saharan Africa: Case Studies from Kenya and South Africa. *Journal of Agricultural Sustainability* 14(3): 120-132.
34. Nelson JA and Bugbee B. 2015. Analysis of environmental effects on leaf temperature under sunlight, high pressure sodium and light emitting diodes. *PLoS ONE* 10: 10. https://doi.org/10.1371/journal.pone.0138930
35. Ochieng M, Mutiso S and Njoroge M. 2021. Emerging Hydroponic Farming Trends in Sub-Saharan Africa: Overcoming Land Degradation and Water Scarcity. *Agricultural Innovations for Development* 12(4): 209-221.
36. Orsini F, Pennisi G, Michelon N, Minelli A, Bazzocchi G, Sanyé-Mengual E and Gianquinto G. 2020. Features and Functions of Multifunctional Urban Agriculture in the Global North: A Review. *In Frontiers in Sustainable Food Systems* 4. Frontiers Media S.A. https://doi.org/10.3389/fsufs.2020.562513
37. Panigrahi CK and Ranasingh N. 2024. Advances in Hydroponic Systems for Efficient Water Use Offer a Sustainable Approach to Modern Agriculture. https://www.researchgate.net/publication/380855167
38. Patel R and Verma S. 2021. Hydroponic Farming in Urban India: Challenges and Opportunities for Small-Scale Farmers. *South Asian Journal of Agriculture* 27(2): 56-67.
39. Payen FT, Evans DL, Falagán N, Hardman CA, Kourmpetli S, Liu L and Davies JA. 2022. How much food can we grow in urban areas? Food production and crop yields of urban agriculture: a meta analysis. *Earth's future* *10*(8): e2022EF002748.
40. Pomoni DI, Koukou MK, Vrachopoulos MG and Vasiliadis L. 2023. A Review of Hydroponics and Conventional Agriculture Based on Energy and Water Consumption, Environmental Impact and Land Use. *In Energies* 16: 4. MDPI. https://doi.org/10.3390/en16041690
41. Pomoni DI, Koukou MK, Vrachopoulos MG and Vasiliadis L. 2023. A review of hydroponics and conventional agriculture based on energy and water consumption, environmental impact and land use. *Energies* 16(4): 1690.
42. Rai P, Bansal A and Saini R. 2020. Hydroponic Systems in South Asia: Addressing Food Security and Sustainable Farming. *Journal of Agricultural Technology* 19(1): 45-58.
43. Rajaseger G, Chan KL, Tan KY, Ramasamy S, Khin MC, Amaladoss A and Haribhai, PK. 2023. Hydroponics: current trends in sustainable crop production. *Bioinformation* 19(9): 925.
44. Rajendran S, Domalachenpa T, Arora H, Li P, Sharma A and Rajauria G. 2024. Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with Emphasis on potato mini-tuber cultivation. *Heliyon*.
45. Rakocy JE, Shultz RC, Bailey DS and Thoman ES. 2023. Aquaponic Production of Tilapia and Basil: Comparing a Batch and Staggered Cropping System.
46. Rathor AS, Choudhury S, Sharma A, Nautiyal P and Shah G. 2024. Empowering vertical farming through IoT and AI-Driven technologies: A comprehensive review. *In Heliyon* 10:15. Elsevier Ltd. https://doi.org/10.1016/j.heliyon.2024.e34998
47. Resh HM. 2013. Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. *CRC Press.*
48. Resh HM. 2013. Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. CRC Press.
49. Ritambara, Shubham and Kaushal S. (2024). Expanding horizons: Exploring the potential of Dutch bucket hydroponics. *International Journal of Research in Agronomy* 7(11): 204-207.DOI: <https://doi.org/10.33545/2618060X.2024.v7.i11c.1962>
50. Rufí-Salís M, Calvo MJ, Petit-Boix A, Villalba G and Gabarrell X. 2020. Exploring nutrient recovery from hydroponics in urban agriculture: An environmental assessment. *Resources, Conservation and Recycling* 155. https://doi.org/10.1016/j.resconrec.2020.104683
51. Salam SB, Shubham and Kaushal S. 2024. Soil management assessment framework for optimizing soil quality. *International Journal of Research in Agronomy* 7(11): 01-06. <https://doi.org/10.33545/2618060X.2024.v7.i11a.1910>
52. Sardare MD and Admane SV. 2019. A review on plant without soil-hydroponics. https://www.researchgate.net/publication/331731460
53. Sati BK, Sharma V and Pant D. 2023. Comparing the pros and perks of hydroponic farming versus traditional agriculture. *Indian Farming* 73(9): 07-10.
54. Shamshad J, Nawaz AF, Khan MB and Arif M. 2024. Climate Change and Food Security. *Environment, Climate, Plant and Vegetation Growth* 265–284. Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-69417-2\_9
55. Sharma N, Acharya S, Kumar K, Singh N and Chaurasia OP. 2018. Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation* 17(4): 364-371.
56. Sharma S, Lishika B, Shahi A and Kaushal S. 2023. Hydroponics: The potential to enhance sustainable food production in non-arable areas. *Current Journal of Applied Science and Technology*, *42*(39), 13-23.
57. Sheibani F, Bourget M, Morrow RC and Mitchell CA. 2023. Close-canopy lighting, an effective energy-saving strategy for overhead sole-source LED lighting in indoor farming. *Frontiers in Plant Science* 14: 1215919.
58. Shivani, Kaur J, Sharma P, Shubham and Kaushal S. 2024. Cultivating Resilience: Exploring Root Systems in Hydroponic Agriculture. *Journal of Experimental Agriculture International* 46(5): 915-925
59. Shrouf A and Alshrouf A. 2024. Hydroponics, Aeroponic and Aquaponic as Compared with Conventional Farming. *American Scientific Research Journal for Engineering*. http://asrjetsjournal.org/
60. Shubham, Kaushal S and Sharma U. 2024. Influence of boron and molybdenum fertilization on brinjal cv. Punjab Bharpoor growth, nutrient uptake, and productivity in alluvial plains of Punjab. *Journal of Plant Nutrition* DOI: 10.1080/01904167.2025.2451925.
61. Shubham, Sharma U and Kaushal R. 2022. Potential of Different Nitrification Inhibitors on Growth of Late Sown Cauliflower Var. Pusa Snowball K-1 and Behavior of Soil NH4+ and NO3- in Typic Eutrochrept Under Mid Hills of NW Himalayas. *Communications in Soil Science and Plant Analysis* 54(10):  1368-1378. DOI: 10.1080/00103624.2022.2146130.
62. Shubham, Sharma U and Kaushal R. 2023. Effect of nitrification inhibitors on quality, yield and economics of cauliflower cv. PSB K1 in Typic Eutrochrept under mid hills of North Western Himalayas. *Journal of Plant Nutrition* 46 (17): 4096-4109.
63. Smith, K., Nguyen, T., and Turner, P. (2020). *Urban Farming Innovations in the U.S.: Scaling Hydroponics for Local Food Production*. Journal of Urban Agriculture, 10(1), 56-68.
64. Stevens JD, Murray D, Diepeveen D and Toohey D. 2024. A low-cost spectroscopic nutrient management system for Microscale Smart Hydroponic system. *PLoS ONE* 19 (5 May). https://doi.org/10.1371/journal.pone.0302638
65. Suhl J, Dannehl D, Kloas W, Baganz D, Jobs S, Scheibe G and Schmidt U. 2016. Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics. *Agricultural Water Management* 178: 335–344. https://doi.org/10.1016/j.agwat.2016.10.013
66. Sun J, Zhou W, Huang D, Fuh JY.H and Hong GS. 2015. An Overview of 3D Printing Technologies for Food Fabrication. *Food and Bioprocess Technology* 8(8): 1605-1615. https://doi.org/10.1007/s11947-015-1528-6
67. Sunny AR, Islam MM, Rahman M, Miah MY, Mostafiz M, Islam N, and Keus, HJ. 2019. Cost effective aquaponics for food security and income of farming households in coastal Bangladesh. *Egyptian Journal of Aquatic Research* *45*(1): 89-97.
68. Suzuki Y and Fujimoto S. 2019. Vertical Farming and Hydroponics: Paving the Way for Future Urban Agriculture in Japan. *Journal of Agricultural Engineering* 47(3): 117-125.
69. Tanaka T and Ishikawa M. 2020. Hydroponic Systems for High-Value Crops in Japan: Exploring Efficiency and Sustainability. *Urban Agriculture and Food Security Journal* 19(4): 233-246.
70. Touliatos D, Dodd IC and McAinsh M. 2016. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. *Food and energy security* *5*(3): 184-191.
71. Tripathi BU and Banda S. 2024. Hydroponics and Aeroponics: Innovative Farming Techniques. https://www.researchgate.net/publication/385741002
72. Van der V, Roos J and Groot J. 2017. Agricultural Innovation and Policy Support for Hydroponics in the Netherlands. *Sustainability in Agriculture* 31(2): 101-112.
73. Velazquez-Gonzalez RS, Garcia-Garcia AL, Ventura-Zapata E, Barceinas-Sanchez JDO and Sosa-Savedra JC. 2022. A Review on Hydroponics and the Technologies Associated for Medium-and Small-Scale Operations. *In Agriculture* (Switzerland) 12: 5. MDPI. https://doi.org/10.3390/agriculture12050646
74. Verma S, Kumar A, Kumari M, Kumar SN, Hansda S, Saurabh A, Poonia S and Rathore SD. 2024. A Review on Hydroponics and Vertical Farming for Vegetable Cultivation: Innovations and Challenges. *Journal of Experimental Agriculture International* 46(12): 801-821. https://doi.org/10.9734/jeai/2024/v46i123190
75. Wang L, Ning S, Zheng W, Guo J, Li Y, Chen X, Ben-Gal A and Wei X. 2023. Performance analysis of two typical greenhouse lettuce production systems: commercial hydroponic production and traditional soil cultivation. *Frontiers in Plant Science* 14. <https://doi.org/10.3389/fpls.2023.1165856>
76. Yamamoto H, Inoue K and Sato M. 2021. Innovations in Hydroponics: Japanese Solutions for Local Fresh Produce in Urban Environments. *Journal of Urban Agriculture* 18(2): 88-99.